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VARIATION IN POPULATION DENSITY OF CICADAS (HEMIPTERA: CICADIDAE) IN THE SYDNEY REGION: *PSALTODA MOERENS* (GERMAR), *THOPHA SACCATA* (FABRICIUS) AND THE 'SPRETA' FORM OF *CYCLOCHILA AUSTRALASIAE* (DONOVAN)

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Abstract

Various sampling strategies were assessed to estimate the population density of emerging nymphs/adult cicadas for three non-periodic species in the Sydney region: *Cyclochila australasiae* (Donovan), *Psaltoda moerens* (Germar) and *Thopha saccata* (Fabricius). Densities for all three species under dry sclerophyll woodland to forest are likely to be 0.5-2/m^2. Density increases as the vegetation becomes more mesic to 2-5/m^2 under rainforest for *C. australasiae*. These densities are similar to other non-periodic species but low when compared with the periodical cicadas, especially *Magicicada septendecim* (Linnaeus) and *M. cassini* (Fisher), of eastern USA. Because of the possible loss of nymphs to predation and dispersion, the most reliable estimates of population density are counts based on emergence burrows. In contrast, counts based on careful searches of exuviae yielded as little as 40% of the burrow count.

Introduction

As part of a longer term study on the effect of soil-transporting fauna on soil formation in the Sydney region of New South Wales, an attempt has been made to measure the amount of soil displaced within the soil and onto the surface (*e.g.* Humphreys 1989, 1994). However, this project has been hampered by a lack of information on the basic ecology of various soil animals. This certainly applies to cicadas, where the below ground activities are known in general terms only (*e.g.* Moulds 1990) and the full life cycle has yet to be determined for any Australian cicada species.

In particular, there is little information on population density, which is required to estimate rates of bioturbation. A similar situation occurs for most cicada species globally and it has only been in the last decade that reasonable information on densities of non-periodical cicadas from a wide range of environments has become available (Dean and Milton 1991, Ewart 2001, Paterson *et al.* 1997, White and Sedcole 1993), although Young (1972, 1975, 1984) had reported earlier on several central American species.

The primary purpose of this paper is to report on estimates of cicada populations at three sites in the Sydney region. Data from two of these sites were obtained more than 20 years ago but have not been published before, although the estimated rates of soil displacement have appeared in summary tables provided by Humphreys and Mitchell (1983) and Paton *et al.* (1995). More recent data have been obtained from the third site. By sampling along an environmental gradient this site provided an opportunity to explore whether or not population density changed with vegetation from drier to moister communities.

A final issue to be considered is the method of estimating populations, which is based mainly on counts of exuviae, adults or emergence holes (termed burrows in this paper), although acoustic methods have been tried also (*e.g.* Paterson *et al.* 1997). To date, the reliability of these methods of counting has not been fully assessed, although there is an obvious need for this since collection of exuviae is largely non-invasive and, hence, a preferred approach in many situations. In contrast, a search for burrows may necessitate site disturbance such as the removal of litter, vegetation and the upper soil layer.

Study sites

The Cattai site, 39 km NW of Sydney, is positioned on the western margin of the Hornsby Plateau at an altitude of 100-120 m a.s.l and receives an average annual rainfall of 900-1000 mm. Glenorie, 5 km to the east, receives an average of 929 mm. A micaceous unit of the Hawkesbury Sandstone gives rise to a Yellow Podzolic (Stace *et al.* 1968: see Table 1 for other soil classifications) on the area examined for cicadas. The natural vegetation consists of dry sclerophyll open forest of *Angophora bakeri*, *Corymbia eximia*, *C. gummifera*, *Eucalyptus punctata*, *E. sparsifolia* and *Syncarpia glomulifera*, with a shrub understorey of *Leptospermum attentuatum* and species of *Acacia*, *Grevillea*, *Hakea* and *Persoonia*.

The Cordeaux site, 64 km SW of Sydney, lies on the Woronora Plateau at an altitude of 320-340 m a.s.l and receives an average annual rainfall of 950-1000 mm. A quartose unit of the Hawkesbury Sandstone gives rise to Earthy Sands and Lithosols. The natural vegetation consists of a dry sclerophyll open forest of *Corymbia gummifera*, *Eucalyptus globoidea*, *E. sclerophylla* and *E. sieberi*, with a shrub understorey of *Leptospermum attentuatum* and species of *Banksia*, *Hakea*, *Isopogon*, *Lambertia*, *Lomatia* and *Persoonia*.

Table 1. Soil classification.

Site	Australian soil classifications			American
	Great Soil Group[1]	Factual Key[2]	new Australian[3]	Soil Taxonomy[4]
Cattai	Yellow Podzolic	Dy2.41	Yellow Chromosol	Haplohumult
Cordeaux	Earthy Sand	Uc5.22	Orthic Tenosol	Dystrustept
Mt Wilson:				
RF & WSF	Krasnozem	Gn3.11	Red Ferrosol	Hapludox
DSF	"	Gn3.21	Brown Ferrosol	"

[1]Stace *et al.* 1968; [2]Northcote 1979; [3]Isbell 1996; [4]Soil Survey Staff 1998.

The Mt Wilson site, 87 km WNW of Sydney, is a hill top at 980 m a.s.l. to the east of an expanse of cleared basalt terrain in the Blue Mountains. Three vegetation communities were sampled: a wet sclerophyll, tall open forest (WSF) on the summit; closed rainforest (RF) on the southern slope 100 m from the summit; and dry sclerophyll open forest (DSF) on the northwestern slope, also 100 m from the summit. The DSF had a tree stratum of *Eucalyptus fastigata* and *Acacia penninervis*, with a shrub layer of *Lomatia* and *Daviesia*. The WSF had an upper tree stratum of *Eucalyptus blaxlandii* and *E. viminalis* and a lower tree stratum of *A. penninervis, Hedycarpa angustifolia* and the tree fern *Cyathea australis*. The RF had a tree stratum of *Acacia melanoxylon, Ceratapetallum apetalum, Doryphora sassafras, Eucalyptus blaxandii, Pittosporum undulatum* and *Quintinia sieberi*. The tree fern, *Dicksonia antarctica,* was conspicuous at the site. A deep, reddish Krasnozem soil, developed on Tertiary basalt, occurred at the first two communities. On the drier site basaltic colluvium overlayed a shale band, possibly a thin remnant of Triassic Wianamatta Group. The nearest long term rainfall records are from Bilpin (14 km to the east) and Mt Victoria (14 km to the southwest), which average about 1459 and 1019 mm respectively. A 26 year rainfall record at Mt Wilson in the early 1900s provided a mean of 1168 mm (McLuckie and Petrie 1927). At all sites the dry sclerophyll forest is particularly fire prone but this effect decreases where the vegetation becomes more mesic.

Identification

Cicada samples from Cattai and Cordeaux were identified by staff at the Australian Museum in 1979. They consisted of the Redeye, *Psaltoda moerens* (Germar) and the Double Drummer, *Thopha saccata* (Fabricius), from Cattai and Cordeaux respectively. Specimens from Mt Wilson were collected in November and December 2002 and identified by the author as the Masked Devil or 'spreta' form of *Cyclochila australasiae* (Donovan), using the descriptions of Goding and Froggatt (1904) and Moulds (1990). These specimens displayed a black abdomen, a tan thorax and head with distinct black markings, including a transverse black bar joining the eyes and a longitudinal black line down the centre of the pronotum and mesonotum (dorsal view) but not across the intervening segment of the pronotal collar. Length of the forewing ranged from 50.5 to 56 mm (n=10, mean 53.5). One example of the yellow form (Yellow Monday) was also found. The ratio of male to female nymphs was 0.91 (n=189), which is similar to many other cicada species in Australia (*e.g.* Ewart 2001) and elsewhere (*e.g.* Young 1975, 1980; White *et al.* 1979).

Methods

Different approaches were adopted to estimate cicada populations. Nymphal exuviae were counted from 10 x 10 m quadrats at Cattai (n=4) and Mt Wilson (n=3). This plot size was selected to match the scale of apparent homogeneity at the site, based on a combination of soil variability and the associated vegetation. Four quadrats were placed side by side around a soil pit at Cattai and the exuviae collected from tree trunks and within a 2 m radius of larger trees, on 26 January 1979. At Mt Wilson (on 31 December 2002) the three quadrats sampled different vegetation types and were positioned adjacent to existing soil pits. This sampling period was at the end of the period of emergence at this site.

The 'spreta' form of *C. australasiae* was first noted at Mt Wilson and on Mt Banks, another basalt cap just to the south, on 28 September 2002. Subsequent visits to Mt Wilson indicated that this species was numerous throughout November and early December. The period of emergence is earlier than that found for *C. australasiae* around Armidale (Coombs 1996). Unlike the Cattai site, however, a systematic search was conducted among shrubs and the litter layer as well as on tree trunks.

Twenty 5 x 1 m quadrats were used at Cordeaux to record the number of dead adults between December 1978 and March 1979. These were the same quadrats used to monitor ant and earthworm activity on a monthly basis between July 1978 and July 1979 (Humphreys 1981). In addition, the number of nymphal burrows was recorded from seven soil pits dispersed over a hectare at Cattai and excavated in early 1979. These pits amounted to a surface area of 10.8 m^2. In order to assess the apparent accuracy of the exuviae counts at Mt Wilson, five random 1 m^2 plots from each of the 10 x 10 m quadrats were carefully searched for additional exuviae and cicada burrows on 13-14 February 2003. These random plots were cleared of ground cover and the soil was carefully scraped away to expose burrows.

Results and discussion

Population estimates based on large quadrat counts

Estimating the population density of cicadas at a site has proved not to be straightforward (Tables 2 and 3). The small sample size, lack of replication and differences in methodology are obvious deficiencies. Even though the 10 x 10 m plot size was selected to match the scale of apparent homogeneity at the site, it became apparent that the distribution of exuviae was not always random. Under RF at Mt Wilson there was some clustering of exuviae on and around the base of a large red stringy-bark (*Eucalyptus blaxlandii*), whereas under WSF and DSF the exuviae seemed to be randomly dispersed, even though each plot contained at least one large tree. At Cattai the four quadrats yielded counts of 0, 2, 8 and 12 and at Cordeaux the 20 smaller quadrats provided total counts from 0 to 3 (7 plots of 0, 7 of 1, 4 of 2 and 2 of 3).

Similar variation has been reported in other studies. Thus, 20 random plots in a woodland of brood II of the periodical cicada *Magicicada septendecim* (Linnaeus) provided a range of densities of 0.7 to 56.7 m^{-2}, with a mean of 5.0 m^{-2} (Dybas and Lloyd 1974). In non-periodical species in the arid Karoo of South Africa, twelve 5 x 5 m plots along a drainage line yielded densities of 9-62 and 2-31 away from the drainage lines (means of 21.9 and 15.2 respectively) (Dean and Milton 1991). In a study in southeast Queensland, 10% of the sample sites contained no exuviae (Ewart 2001). In comparison, the neotropical cicada *Procollina biolleyi* is reported to be uniformly distributed in a humid montane forest site in Costa Rica away from trail edges. In contrast, a less numerous and smaller species at the same site, *Carinetta spinocosta,* exhibited a patchy distribution (Young 1975), although no data were provided to quantify this. However, in a subsequent study involving a lowland species, *Zammara smaragdina*, considerable spatial variation in density was noted, with individual plots varying by an order of magnitude or more in seven of the ten sampling dates (Young 1980). Young (1980) also noted that about 15% of the total population came from one of 23 plots and that some of these other plots yielded counts of <0.5%.

Table 2. Population estimates at Cattai and Cordeaux in dry sclerophyll vegetation.

Site	Plots	Species	Total plot area (m^2)	Sample type	Density (n/ 100 m^2)
Cattai	A-D	*Psaltoda moerens*	400	exuviae	5.5
Cattai	soil pits*	*Psaltoda moerens*	10.8	burrows	148
Cordeaux	A-T	*Thopha saccata*	100	adults	21

* in addition there was one trapdoor spider burrow.

Table 3. Population estimates of *C. australasiae* at Mt Wilson.

Parameter	Density per ha under different vegetation types (n/100 m^2)		
	Dry sclerophyll	Wet sclerophyll	Rainforest
(a) No. of exuviae in 10x10 m plot	11	73	106
(b) No. of additional exuviae from 1x1m plots*	40	100	80
(c) Total No. of exuviae [= (a) + (b)]*	51	173	186
(d) No. of burrows from 1x1m plots*	80	160	460
(e) Proportion of total exuviae to burrows [=100 (c) / (d)]	63.8%	108.1%	40.4%
Estimated population	50-100	150-200	200-500

*scaled to 100 m^2.

Population estimates based on exuviae compared with burrows

There is also a pronounced difference between exuviae and burrow counts. This was greatest at Cattai, where the burrow count exceeded the exuviae count by a factor of 25 (148 *v.* 5.5 per 100 m^2, Table 2). Apart from possible loss by predation (see below), this difference might be attributed to one or more reasons. Firstly, the exuviae count was confined to the larger trees only and ignored the surrounding understorey. Secondly, the soil pits may have been biased to sites of unusually higher density, though there is no obvious reason that this should be so. Thirdly, the burrows may include nymphs other than the last instar. However, as most of the burrows contained a sizable nymph it indicates that they were mostly at the final instar stage. Furthermore, it is thought that most burrowing takes place during the final instar phase and within a few months of ecdyis, as demonstrated for the periodical cicada (Cory and Knight 1937). Thus, even if it is assumed that only half of the burrows contained final instar nymphs, the density is still much higher than exuviae counts suggest. It was partly this discrepancy between exuviae and burrow counts at Cattai that lead to the sampling regime pursued at Mt Wilson. Nevertheless, the results at Mt Wilson also established that burrow count exceeded the initial exuviae count but by a reduced level of between 1.6 and 5.8 (Table 3, row 'd' to 'b'), which was further reduced to <2.5 for the total exuviae count (Table 3, row 'd' to 'c'), although on the wet sclerophyll plot the exuviae count slightly exceeded the burrow count.

A similar degree of variation between exuviae and burrow counts was reported by Strandine (1940) for the periodical cicada. Nevertheless, the reduction in the discrepancy still leaves a sizable difference in density. It would seem that the type of exuviae count undertaken in the present study provides a moderately accurate estimate of the probable nymphal population that is correct at the order of magnitude level and that small plots, stripped of ground cover and litter, yield a better estimate than is obtained from searching larger plots where the vegetation cover is left undisturbed. Thus, at Mt Wilson the total exuviae count estimated 40->100% of the burrow count (Table 3, row 'e') but for the initial exuviae count the estimate was only 13 to 46% (Table 3, row 'a' to 'e'). Unfortunately, the variation exhibited between the three vegetation types is not conducive to determining realistic correction factors. Perhaps the most reliable method is to use cages to catch emerging nymphs (*e.g.* Young 1980) but this approach requires monitoring at frequent intervals and may not be suited to remote sites.

A possible reason for the discrepancy between exuviae and burrow counts is predation, for it is well known that emerging nymphs and adults are eaten by birds (*e.g.* Young 1984, Ewart 2001). For example, the population count at the Cordeaux site consisted of dismembered adults of *Thopha saccata*, of which the abdomen appears to have been the main food item. In North America there are several reports describing the voracious appetites of birds feeding on emerging and adult periodical cicadas, so much so that for periods of up to several weeks all cicadas may be consumed (Beamer 1931, Lloyd and Dybas 1966). In addition, it is possible that exuviae are dispersed by wind and rain and therefore removed from the sample plot. Nevertheless, loss from one plot must lead to gain elsewhere and hence if an adequate sample size is employed this effect should balance out, although it may explain some of the variation in counts between individual plots.

Comparison of population density and periodicity

Because of these differences and unresolved issues, the population density at Mt Wilson is expressed as a range of 0.5-1 m^{-2} under dry sclerophyll vegetation, 1-2 m^{-2} under wet sclerophyll and 2-5 m^{-2} under rainforest. At Cattai the density of *Psaltoda moerens* was probably around 1-2 m^{-2}, whereas the *Thopha saccata* data are insufficient to suggest a realistic estimate. These densities are very low in comparison to the well studied periodical cicadas, which commonly attain densities >10 m^{-2} and sometimes >100 m^{-2} (*e.g.* Dybas and Davis 1962, White *et al.* 1979), although in some cases the densities were much lower even at sites which are considered to contain high populations (*e.g.* Dybas and Lloyd 1974). Nevertheless, large population densities attained by *Magicicada* spp. are thought to be in part a product of behavioural passiveness, whereby adults make no attempt to avoid predators or capture.

Population densities of other non-periodical cicadas in North America are thought to be much smaller (Beamer 1931, Lloyd and Dybas 1966), which would make them similar to the three Sydney species considered in this study and to other non-periodical cicadas from a wide range of environments where densities are typically <1 to 5 m^{-2} (Table 4). An exception to this was the average density of 10.6 m^{-2} recorded in 1973 for *Procollina biolleyi* in the highlands of Costa Rica, which contrasts with other neotropical species which are mostly <3 m^{-2} (Young 1975, 1980). The high population density by a non-periodical species may imply causal factors other than the predator-prey explanation noted above.

Although less well studied, non-periodical cicadas appear to exhibit some level of emergence each year, usually in a preferred season but with higher numbers appearing every few to several years. This seems to apply to larger taxa, at least, and implies the existence of an emergence and survival strategy different from the periodical cicadas, with their well recognised and very predictable 13 or 17 year broods. However, although a degree of periodicity occurs in at least some non-periodic taxa, the fact that it has rarely been demonstrated may indicate that the pattern, if it exists, is somewhat irregular. For the three Sydney species examined in this study the degree of periodicity is not known with any certainty, although it is thought that *Cyclochila australasiae* has a 6-7 year cycle (Moulds 1990). This could reflect a partial influence of ENSO (El niño - Southern Oscillation quasi-periodic climate cycle) events in which lower survival in drought years is expected, especially if fire occurs in the period just after eggs are laid. Detailed analysis of the Southern Oscillation indicates a strong periodicity of 6 years with weaker 3, 3.8 and 10-12 year cycles in Australia (Burrows 1992). In Southern Africa the strongest ENSO periodicity is about 18 years, which is similar to the period between the last two recorded emergences of *Quitillia* cf. *conspersa* in *c.* 1972-3 and 1988-9 (Dean and Milton 1991). This climatic link does not easily apply to the periodical cicada as there are no known 13 or 17 year climatic cycles (Burrows 1992) and because different broods, although operating at 13 or 17 years, exist in different calendar year cycles.

Table 4. Comparison of non-periodical cicada population estimates (quoted on a hectare basis as is common in international literature).

Location and environment	Species	Mean [and Variation] (No/ ha)	Reference
Karoo, Southern Africa; arid shrubland	*Quintillia* cf. *conspera*	7,400 [se 1,036]	1
New Zealand; sub-alpine	Guild of 6 species	10,100 [range: 865-20,000]	2
Arizona; riparian zone in arid setting	*Diceroprocta apache*	50,000 [range: 7,000-118,000]	3
Tuscany; Mediterranean pine forest & olive grove	*Cicada orni*	33,660 [se=5,285] 13,201 [se=3,551]	4
SE Queensland; humid sub-tropical; coastal WSF	*Psaltoda plaga, P. claripennis* & 4 others	8,370 [nd]	5
Costa Rica; humid tropics; secondary montane RF	*Procollina biolleyi*	105,800 [nd, but var]	6
Costa Rica; humid tropics; lowland RF	*Fidicina sericans*	93,000 [nd, var]	7
	F. spinocosta	15,000 [nd,var]	
	Zammara smaragdina	11,700 [8,000-17,300]	
Cattai, Sydney; humid temperate; DSF	*Psaltoda moerens*	550 [range: 0-1,200] 14,800 [nd]	8
Cordeaux, Sydney; humid temperate; DSF	*Thopha saccata*	2,100 [range: 0-6,000]	8
Mt Wilson, Blue Mts; humid temperate; DSF, WSF and RF respectively	*Cyclochila australasiae*	8,000 [5,000-10,000]* 16,000 [15,000-20,000]* 46,000 [20,000-50,000]*	8

[1]Dean and Milton 1991; [2]White and Sedcole 1993, using unadjusted density figures (see Lane 1993); [3]Andersen 1994; [4]Patterson *et al.* 1997; [5]Ewart 2001; [6]Young 1975; [7]Young 1980; [8]this paper. se = standard error; nd = not determined; var = variable; * = estimate (see text).

Population variation along an environmental gradient

There was a noticeable increase in density of *C. australasiae* with the moisture status of the vegetation at Mt Wilson, *i.e.* from dry sclerophyll to wet sclerophyll and thence rainforest. This trend was apparent regardless of the measure used, *i.e.* initial exuviae count, corrected exuviae count or burrow count (Table 3, rows (a), (c) and (d) respectively). This result implies that habitat differences exert a strong influence on population density. The strength of this relationship was tested on the best quality data at this site, *viz.* the burrow densities. The burrow data satisfied the Ryner-Joiner test for normality (R: 0.9851, P >0.1000) and the Bartlets test for homogeneity (P-value 0.895) and thus indicated an adequate sample size. Based on one-way ANOVAs and Fisher pair-wise test, the burrow density in the RF was significantly different from both the WSF (P=0.018) and DSF (P= 0.004) but the latter two could not be separated (P=0.397), despite the mean of the WSF being twice that of the DSF site. Presumably the rainforest provides a better or more stable habitat in terms of maintaining food supply and/or a reduced impact from predators. If Australian cicada species are xylem feeders, as demonstrated for the periodical cicadas (White and Strehl 1978), a habitat less affected by dry conditions and therefore pronounced water stress on plants, may favour survival of nymphs and therefore yield greater populations. It is noteworthy that the sampling at Mt Wilson occurred during a prolonged drought (late 2002) but, even so, the clayey soil at both the wet sclerophyll and rainforest communities, which contained large earthworms (5-8 mm diameter and 200-300 mm long), was much moister than at the dry sclerophyll site. Whether or not it is moisture availability and hence greater plant vigour that is significant or some other factor remains to be evaluated. Young (1984) suggested a strong cicada - legume tree host association in the humid neotropics on the assumption that the xylem fluid from legumes was more nutritious than other host trees. As Young (1984) noted, the same might apply to trees with micorrhizal associations and this raises a tantalising prospect in Australia, as many eucalypts and closely related genera possess micorrhiza.

It is interesting to note that similar population densities occured under the same vegetation structural type and when the same type of measure was applied, despite different species and locations. This is evident in the general survey under dry sclerophyll forest, where densities of 5.5, 11 and 21/100m^2 occurred at Cattai, Mt Wilson and Cordeaux respectively (Tables 2 and 3). Of the three species considered, *Thopha saccata* is the largest cicada in Australia and the other two species fall within the large size group for Australian taxa. Thus it seems that a similar habitat, which in this case is a dry sclerophyll forest, may exert a similar set of constraints on cicada populations, although this may be conditional on species of similar size being compared. This assumes, of course, that the three species were studied at the same life stage, *i.e.* at peak emergence. Whether or not this was the case is uncertain except to note that the attempts to record population in the 1978-79 summer (Cattai and Cordeaux) and the 2001-02 summer (Mt Wilson) were prompted by the observation that cicada activity was particularly pronounced on those occasions.

Conclusions

Population densities for three large cicada species in the Sydney region were estimated to be 0.5-2/m^2 under dry sclerophyll forest at three different locations. An increase in density was shown for one species, *C. australasiae*, as the vegetation assumed a more mesic character, reaching 2-5/m^2 under rainforest. These densities were similar to many other non-periodic species but up to one or two orders of magnitude less than those reported for the periodical cicadas in North America.

Of the methods used for estimating population density counts, burrows gave the highest values and, hence, were considered to be most reliable. However, when this option is not feasible, such as when disturbance of the litter layer or surface soil is not desired, a count based on exuviae provided an estimate that was at least 40% of the burrow count.

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